

A search for kilogauss magnetic fields in white dwarfs and hot subdwarf stars

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ABSTRACT

We present new results of a survey for weak magnetic fields among DA white dwarfs with inclusion of some brighter hot subdwarf stars. We have detected variable circular polarization in the $H\alpha$ line of the hot subdwarf star Feige 34 (SP: sdO). From these data, we estimate that the longitudinal magnetic field of this star varies from -1.1 ± 3.2 kG to $+9.6 \pm 2.6$ kG, with a mean of about +5 kG and a period longer than 2 h. In this study, we also confirm the magnetic nature of white dwarf WD1105-048, found earlier in a study by Aznar Cuadrado et al. (2004), and present upper limits of kilogauss longitudinal magnetic fields of 5 brightest DA white dwarfs. Our data support the finding of Aznar Cuadrado et al. (2004) that $\sim 25\%$ of white dwarfs have kilogauss magnetic fields. This frequency also confirms results of early estimates obtained using the magnetic field function of white dwarfs (Fabrika & Valyavin 1999).

Subject headings: stars: individual (Feige 34, WD1647+591, WD1105-048)—stars: magnetic fields — stars: white dwarfs

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1. Introduction

The investigation of white dwarf stars (WDs) is of fundamental importance for the understanding of stellar and galactic evolution, as WDs represent the final evolutionary stage of more than 90% of all stars. Nowadays, we believe that the general properties and evolution of WDs are fairly well understood. However, there are several important problems that still need to be properly addressed, especially those connected with the group of about one hundred isolated magnetic white dwarfs (MWDs) (Angel et al. 1981; Schmidt & Smith 1995; Liebert et al. 2003; Valyavin et al. 2003; Aznar Cuadrado et al. 2004). The first problem is related to the origin of the MWDs. Earlier studies (Angel et al. 1981) suggested that MWDs are descendants of magnetic Ap/Bp stars. More recent studies, however, have suggested that the progenitors are not restricted to this class (Liebert et al. 2003; Kawka & Vennes 2004; Wickramasinghe & Ferrario 2005). The second problem is associated with the evolution of a global magnetic field during a WD’s life: it has been shown (Liebert & Sion 1979; Fabrika & Valyavin 1999; Valyavin & Fabrika 1999; Liebert et al. 2003) that the magnetic field exhibits some peculiar features during the WD life time. One of them is that WDs with strong fields show a tendency to increase in fractional incidence with age, in contradiction to the hypothesis that WD magnetic fields decay with time (Wendell et al. 1987).

Another group of problems is related to astroseismology of WDs. A model analysis of pulsation modes applied to pulsating WDs (Winget et al. 1994, for instance), theoretical exploration (Markiel et al. 1994), and high-resolution spectroscopy (Koester et al. 1998) suggest the general presence of kilogauss magnetic fields in pulsating white dwarfs. In spite of that, attempts to measure magnetic fields in pulsating WDs (Schmidt & Grauer 1997, for instance) have yielded no positive results, suggesting that the theory of WD pulsation may require revision.

The implications of these studies are extremely significant. Unfortunately, *they are based on a highly biased and limited sample of strongly magnetic WDs*, and therefore they are still controversial and require better statistics (Liebert et al. 2003). It appears quite likely that the fraction of MWDs (as compared to the total population of known WDs) will increase significantly if high-precision spectropolarimetric surveys are conducted. The required accuracy of magnetic field measurements is about 1 kG or better (Liebert et al. 2003).

In order to better understand the origin of magnetic fields in late type stars, it is also interesting to extend observations to the group of hot subdwarfs, the magnetic nature of which has already been reported (Elkin 1996; O’Toole et al. 2005), but which is still not well studied. The importance of a study of hot subdwarf stars to the theory of stellar evolution is

established by the fact that they exhibit a variety of evolutionary channels to the white dwarf stage (Greenstein & Sargent 1974; Heber 1986; Saffer et al. 1994; Williams et al. 2001a,b; Maxted 2004). A search for magnetic fields among these stars should help to understand the magnetic nature of some low- normal-mass magnetic white dwarfs which potentially could be evolutionary products of the subdwarf stars. In particular, the study of a heterogenous group of sdO stars (Maxted 2004, and references therein) for which it has been found that about 65% of them may be unresolved binary systems (Williams et al. 2001b), makes it possible to consider dynamo-induced magnetic fields in these systems, suggesting a non-fossil field origin in their magnetic white dwarf descendants.

For these reasons, we are carrying out an observational program with the 6 m and 8 m Russian and European telescopes. The main goal of the project is the accumulation of observational data on white dwarf magnetism in the kilogauss region and statistical analysis of these data for a study of the evolution of magnetic fields in degenerate stars. Our secondary goals are monitoring studies of some individual weak-field magnetic WDs (Valyavin et al. 2005) and some individual brighter hot subdwarf stars. Here, we discuss new results from our survey. We present the positive detection of a kilogauss longitudinal magnetic field on the sdO star Feige 34 and confirm the magnetic nature of white dwarf WD1105-048, detected recently by Aznar Cuadrado et al. (2004). We also suspect the presence of a varying weak longitudinal magnetic field on the pulsating white dwarf WD1647+591.

2. Selection of the sample and observational strategy

At the present stage, our study of hot subdwarfs is restricted to observations of only one of the brightest objects Feige 34. Our observations of white dwarfs are aimed mainly at studying a random sample of WDs in a limited space volume with an accuracy of magnetic field measurements of about 1-2 kG and better. To answer the question of *whether WD magnetic field evolution can be detected in observations*, it is important to extend field measurements with uniform accuracy to the whole range of WD masses and temperatures. All types from the hottest (youngest) WDs to the coolest (oldest) degenerates of DA8-9 spectral classes are present in our list, in order to provide the survey with appropriate statistics.

With the aid of the 6 m telescope (BTA), we searched for circular polarization in cores of the hydrogen lines of the brightest ($V < 14$ mag) northern hot (young) WDs and WDs of intermediate temperatures. The cooler (and older) WDs, however, can not be studied well with this telescope. These stars are intrinsically fainter and have weaker Balmer absorption features that make it difficult to study them polarimetrically with the necessary field measurement accuracy. In order to minimize this observational bias, we have extended our list

toward observations with the VLT of a random sample of southern WDs with $T_{\text{eff}} < 9000 \text{ K}$. These observations, when completed, will make it possible to determine the fractional incidence of magnetism in the low-field regime among WDs of different ages. Our full list consists of 40 isolated WDs of different masses and temperatures. As follows from Fabrika & Valyavin (1999) and from the discussion presented by Aznar Cuadrado et al. (2004), the fractional incidence of magnetism in the region from 1 kG to 10 kG is expected to be a few to several tens of percents. Aznar Cuadrado et al. (2004) give an estimate of 25%. Their conclusion, if true, suggests that weak magnetic fields may be found in about 10 WDs in our list at a detection level around 1 kG. These data, combined with those obtained for the group of strongly magnetic MWDs, will then be used to determine unbiased relative fractions of young and old MWDs, to be compared for a study of the evolution of WD magnetic fields.

In this paper, we report observations of the 6 brightest WDs and one subdwarf star in our target list for the 6 m telescope. Although the survey is not yet complete, new weak-field magnetic stars are interesting enough to warrant a separate paper concerning the brightest, hot WDs and WDs of intermediate temperatures. These data represent our first scientific observations obtained with a new polarimeter (see next section). White dwarfs presented here may also be considered as a random sample, to be compared with data presented by Aznar Cuadrado et al. (2004). The full survey, including the data from the VLT and a final, detailed statistical analysis will be presented later.

3. Observations and data reduction

The observations were carried out at the 6 m Russian telescope from 2003 to 2005 in the course of about 9 observing nights shared with other observational programs. The observations are now obtained using the updated prime-focus spectrograph-polarimeter UAGS ($R \sim 2000$, $H\alpha$ region). The instrument and observational technique are described in detail by Afanasiev et al. (1995) and by Naydenov et al. (2002). The modulation technique we use in observations with this instrument, the strategy of the observations, and the data reduction are very similar to those performed by Bagnulo et al. (2002) and described by Valyavin et al. (2005).

In polarimetric observations of each star, we obtain series of short, consecutive exposures at two orthogonal orientations of the quarter-wave plate (the sequence of its position angles is $+45^\circ, -45^\circ, -45^\circ, +45^\circ$). Assuming *a priori* that the time-scale of possible variability of the longitudinal magnetic field could be as short as a few minutes, we usually set the integration time of each exposure to 60-300 s, depending on stellar magnitude and sky conditions.

For longitudinal magnetic field measurements, we initially use cross-correlation analysis of the displacement between positions of the $H\alpha$ line in spectra of opposite circular polarizations (Monin et al. 2002; Valyavin et al. 2005). Applying this method to the series of short time exposures, we then analyze rows of the longitudinal field values to rule out a possible variability of the magnetic field on longer time scales (tens of minutes and longer). After the determination of these scales for each star, we combine spectra of equal orientations of the quarter-wave plate into longer equivalent exposures and build Stokes I and V profiles as described in Valyavin et al. (2005).

Finally, we obtain the longitudinal field determinations from the Stokes I and V profiles through the weak-field approximation, as described by Bagnulo et al. (2002). Associated error bars are obtained by using the Monte Carlo modeling method demonstrated by Schmidt & Smith (1994).

4. Results

Results of longitudinal magnetic field measurements are summarized in Table 1, where column 1 is the name of the WD, column 2 is the spectral class, column 3 is the Julian Date of the midpoint of the observation, column 4 is the exposure time, and columns 5-6 report the measurements and uncertainties of the longitudinal magnetic fields as obtained using the weak-field approximation. The Stokes I and V spectra are illustrated in Figure 1.

Six targets of our list (WD0009+501, WD0644+375, WD0713+584, WD1105-048, WD1134+300, WD1647+591) have already been observed by Schmidt & Smith (1994, 1995); Valyavin et al. (2003); Aznar Cuadrado et al. (2004); Valyavin et al. (2005). In order to minimize the probability to observe a possible zero crossover of the longitudinal magnetic field due to rotation, we repeated the observations of these WDs.

In order to clarify our polarimetric measurements, here we also present an example of our observations of the magnetic white dwarf WD0009+501 (Valyavin et al. 2005). The field of WD0009+501 varies with the rotation phase from about -120 kG to about +50 kG (Valyavin et al. 2005). Here, we use its phase-resolved Stokes I and V spectra at the maximum field obtained during JD245300(3-8). As one can see, the comparatively weak magnetic field (50 kG) of this faint (for spectropolarimetry) WD ($V = 14.4$) can easily be resolved and measured in our observations.

Two targets in our list WD1105-048 and Feige 34 showed longitudinal magnetic fields by the presence of weak circular polarization in the $H\alpha$ cores of their spectra. We briefly discuss these results.

Feige 34 or **WD1036+433** (McCook & Sion 1999) is one of the brightest ($V = 11.22$) weak-lined subdwarf stars spectroscopically classified as sdO (Greenstein & Sargent 1974; McCook & Sion 1999, and references therein). Thejll et al. (1991, 1995) suggested this star to be a close binary system having a companion of spectral type K. In three observations of this star in different nights, the longitudinal magnetic field was detected once at more than the 3σ level (see Table 1). S-shaped circular polarization is seen in one of the observations (at JD=2453005.49; see Fig. 1). We therefore conclude that WD1036+433 may be another one candidate to magnetic subdwarf stars (Elkin 1996; O’Toole et al. 2005) with a weak magnetic field. The peak field is below 10 kG. In our observations, the field varies in the range from -1 kG to +9.6 kG, due to possible rotation with a period longer than 2 hours.

WD1105-048 is, in comparison, a well-studied, ordinary DA3 WD (McCook & Sion 1999) discovered recently as magnetic by Aznar Cuadrado et al. (2004). The longitudinal magnetic field of this star was found to be variable, varying from about -1 to -4.6 kG. In this study, we confirm the magnetic nature of this degenerate star. In the course of two consequent nights, WD1105-048 showed a variable longitudinal field, from 0 to about -8 kG. From our data, the rotation period is longer than 3 hours.

In addition, we have selected 2 white dwarfs.

WD1647+591 is a representative of the group of pulsating WD stars, the magnetic nature of which has been discussed by a number of authors (Schmidt & Grauer 1997, and references therein). Earlier observations of the longitudinal magnetic field (Schmidt & Grauer 1997) yielded null results at a level of about 3 kG. However, the probability to observe a possible zero crossover of the field due to rotation of the star was quite high in those observations. In particular, their results and conclusions are based on only three measurements with associated error bars of 1.1, 1.2 and 5.7 kG. These three observations, obtained in different years, together with the indirectly estimated rotation period of about 9 hr (Schmidt & Grauer 1997, and references therein) do not exclude a situation that the observations have been obtained close to the crossover. For this reason, we continued observations of WD1647+591. The data showed no detection above the 3σ level. Just one of the observations showed a 2.7σ detection at JD2453195.46. Unfortunately, poor weather conditions limited our observations of this star, making it necessary to continue the monitoring.

WD 0501+527 is one of the interesting WDs in our list. In the high-resolution observations of this star Reid & Wegner (1988) have found a weak emission line at the $H\alpha$ core. Reid & Wegner (1988) have argued that the observed emission can not be due to a nearby red dwarf companion, suggesting a photospheric origin. Explaining this emission feature they tested an atmosphere model under the assumption of a chemically stratified atmosphere which can produce the necessary temperature inversion giving rise to emission

cores in the Balmer lines (Reid & Wegner 1988, and references therein). The presence of magnetic fields in this object, if detected, could potentially be interesting for alternative, magnetoionic heating models of the observed emission (Greenstein & McCarthy 1985, see their discussion). High-resolution spectra presented by Reid & Wegner (1988) make it possible to estimate roughly the surface magnetic field on WD 0501+527 to be less than 100 kG. In our observations we estimate its magnetic field to be weaker than 10 kG.

The magnetic field estimates in the spectra of the other observed stars did not yield any detections. Unfortunately, due to weather conditions and technical limitations which require us to carry out the observations only in the $H\alpha$ region, we did not achieve the required accuracy better 2 kG for all the stars. Nevertheless, the possible detection of the longitudinal magnetic field in WD1036+433 and the confirmation of the magnetic nature of WD1105-048 make it possible to contribute to the ongoing discussion about the fractional incidence of WD magnetism in the kilogauss region.

5. Discussion and conclusion

We have presented new observations of kilogauss longitudinal magnetic fields in 6 WDs and one hot subdwarf star. We confirm the magnetic nature of WD1105-048 and find a new candidate weak-field sdO star, Feige 34 (WD1036+433). We did not detect any significant field in the pulsating WD WD1647+591; nevertheless, we find it important to note that the 2.7σ result (at JD2453195.46), as well as the systematic negative magnetic field in all of our observations and those of Schmidt & Grauer (1997) may indicate the presence of a weak, varying, or fluctuating non-zero longitudinal magnetic field. It should also be noted that recent high-resolution spectroscopy of WDs (Koester et al. 1998) showed significant broadening of $H\alpha$ cores in the spectra of pulsating ZZ Ceti WDs with typical projected velocities of 30 – 40 km/s. Such velocities seem to be in conflict with astroseismology (Koester et al. 1998) and support independently the probable presence of alternative broadening mechanisms such as a kilogauss magnetic field. For this reason, we hope that polarimetric observations of WD1647+591 will be continued.

Together with another subdwarf stars the magnetic nature of which has been recently detected (Elkin 1996; O’Toole et al. 2005), the presence of kilogauss magnetic field on Feige 34, if confirmed by future observations, would be of a great interest for theories of the origin of hot subdwarfs. Despite the fact that Zeeman polarimetric observations of these stars are relatively uncommon in the literature, such a high rate of positive detections suggests that the presence of global magnetic fields may be a typical property of the hot subdwarfs (by analogy with the Ap/Bp stars). At this moment, the origin of magnetic fields in these stars

is unclear (O’Toole et al. 2005). These fields may be fossil remnants of their progenitor fields or dynamo-generated by any unknown mechanism. In this connection, the suggested (Thejll et al. 1991, 1995) binarity of Feige 34 gives new interesting possibilities to explain the magnetic nature of this object. Following the accretion model of helium degenerate dwarf formation in a close binary (Iben & Tutukov 1986) we may speculate that the kilogauss magnetic field could be generated by the accretion processes which might take place in Feige 34. This assumption, if true, could then explain the origin of some kilogauss-strength magnetic fields in low-mass white dwarfs which may potentially be products of the evolution of the sdO stars.

Kilogauss upper limits are presented for the other 5 WDs. Here, we formally estimate the fraction of kilogauss MWDs as 17% (1/6) that is consistent with the estimate of Aznar Cuadrado et al. (2004) (25%). Note, that practically the same estimate of the frequency of kilogauss MWDs has been done using the magnetic field function technique (Fabrika & Valyavin 1999). Based on these results, one might speculate that the MWDs are not a unique class of degenerate stars, but rather represent the strong-field tail of a continuous distribution of field intensities. The 10 % fraction of megagauss MWDs (Liebert et al. 2003), in comparison to 25 % for kilogauss fields, supports this idea. This conclusion, however, could be more definite if framed in terms of surface magnetic fields (mean field modulus, B_s) since our study is based on observations of only the longitudinal component B_l of the field, which is smaller than B_s in all cases. In case of a dipolar geometry, the difference may be as much as 3 times and higher, depending on the orientation of the dipole to the line of sight. Furthermore, the large-scale magnetic field structure of the weak-field MWDs may be different from dipolar, giving a very strong observational bias to the underestimation of the incidence of WD magnetism in the polarimetric observations. Therefore, the above conclusion about the incidence of magnetism below 1 kG can only be considered as a lower limit (see also Aznar Cuadrado et al. (2004)).

Assuming magnetic field conservation during MS star evolution into a WD, we have to conclude that the majority of MWDs (namely those with kilogauss field strengths) descend from MS stars with global magnetic field strengths even weaker than 1 G, much weaker than those of Ap/Bp stars (Putney 1999), for which dipole fields larger than about 300 G (Aurriere et al. 2004) are found. So, we may assume that stars other than Ap/Bp stars evolve into kilogauss MWDs (Kawka & Vennes 2004; Aznar Cuadrado et al. 2004; Wickramasinghe & Ferrario 2005). Alternatively, we should conclude that significant flux loss occurs during the post-main sequence evolutionary process, although this is unlikely to be consistent with the newly found, high fraction of MWDs compared to the few percent fraction of Ap/Bp stars on the upper main sequence. Further examination of these two possibilities will be among the goals of our more detailed study upon completion of our survey.

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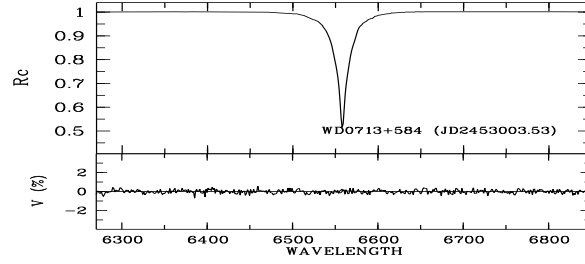
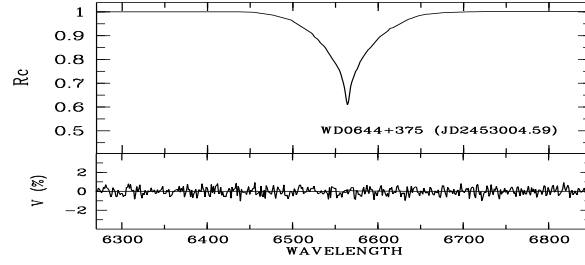
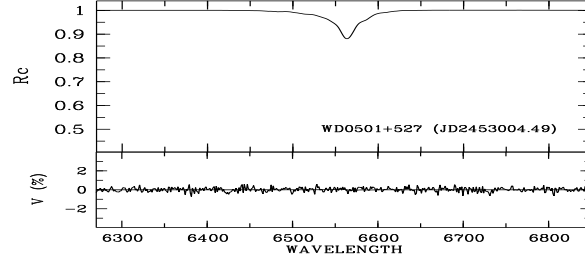
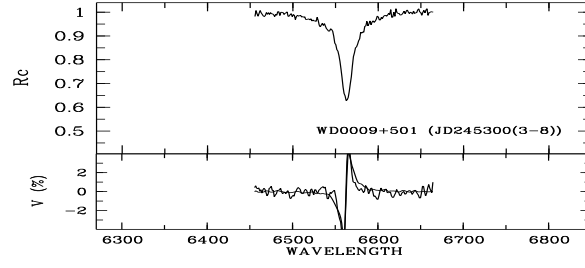
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Table 1. Determination of the mean longitudinal field obtained as explained in § 3.

Name WD	SP	JD (-2400000)	Exp (sec)	B_l (kG)	σ (kG)
0501+527	DA1	53004.49	3600	-3.9	2.8
0644+375	DA2	53004.59	4020	+1.9	1.8
0713+584	DA4	53003.53	7100	+0.6	0.8
		53003.61	7100	+0.8	1.0
		AVERAGE		+0.7	0.6
1036+433	sdO	53005.49	6000	+9.6	2.6
		53005.63	5000	+5.9	2.8
		53422.34	5500	-1.1	3.2
		AVERAGE		+5.5	1.6
1105-048	DA3	53006.54	3600	-7.9	2.6
		53007.55	7200	-4.8	2.3
		53007.64	3100	+0.1	2.7
		AVERAGE		-4.4	1.4
1134+300	DA3	53004.64	1800	+8.9	4.5
		53006.62	3600	+3.5	2.7
		AVERAGE		+4.9	2.3
1647+591	DAv4	53194.47	3600	-2.9	3.4
		53195.46	3600	-8.7	3.2
		53422.59	5100	-0.5	2.8
		AVERAGE		-3.8	1.7



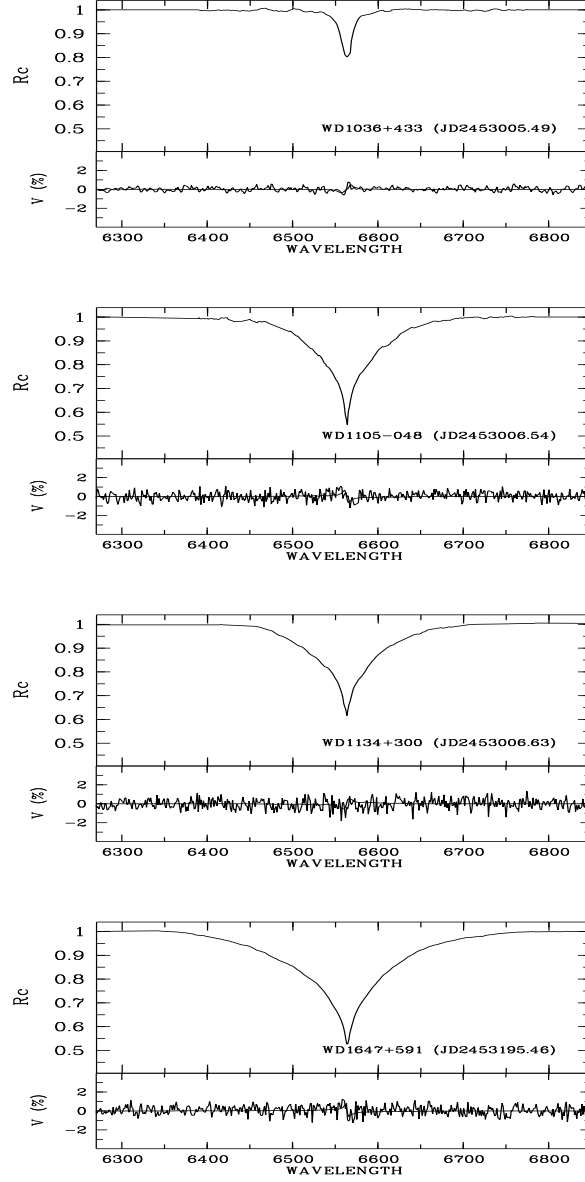


Fig. 1.— Stokes I and V spectra of observed WDs at the $H\alpha$ core. The weak-field fit of the Stokes V spectra is illustrated by thick lines.